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Contents

Introduction

This document presents the activities carried out with the LISA system during the winters 2005-2006 and 2006-2007 in the ski resort of Alagna Valsesia (Italy, Piedmont region), in collaboration with the technical personnel of the ski resort (Monterosa 2000 S.p.A) and the local Alpine Guides.

The main results as well as some future lines on this campaign are also outlined. Results include the systematic identification and classification of avalanches, visualization of skiers' tracks, production of hazard maps and the generation with the LISA instrument of a digital elevation map of the area.

Note that sometimes paths or filenames appear in the document in italic style, as for example *DataAlagna\DataProcessed\Avalanches*. These paths refer to the contents of the DVD accompanying to this document. The document itself can also be found in PDF format at the root folder of the DVD.

The LISA instrument

The instrument, LISA (acronym for Linear SAR), is a ground based linear synthetic aperture radar (GB-SAR) fully developed and built at the Joint Research Centre (Ispra, Italy). The radar is mounted in a temperature-controlled container for ease of transportation and deployment, as can be seen in Figure 1.

Figure 1: Outside view of the LISA instrument at Cimalegna

A schematic and a picture of its components, instead, can be seen in the Figure 2. The main component of the instrument is a vector network analyzer (VNA in the figure), which is used to generate the stepped-frequency continuous wave radar pulses and receive the coherent responses. A sled carrying the network analyzer, the power amplifier (AMP) and the antennas (Tx, Rx1 and Rx2) slides along a rail 2 m long in order to synthesize a linear aperture such that the azimuth resolution is obtained. This movement is directed by a linear positioner (LP) by means of a serial interface and the appropriate control software. Two external hard disks (HD1 and HD2) implement the data archiving and backup, while the visualization of the instrument inside the container and outside (radar field-of-view) is performed thanks to two Ethernet video cameras (WC1 and WC2). A meteorological station (METEO) controls the temperature, pressure and humidity of the instrument inside the container. A personal computer (PC) operates all the systems and is used for the data processing. An uninterrupted power supply (UPS) warranties a stable power line, allowing a continuous operation of the instrument even under shorts cuts of energy. Isolation against current discharges coming from the external Ethernet connection is also performed through the UPS.

Connectivity to the outside is necessary for monitoring the proper operation of the radar from the headquarters at Ispra. It is performed through two different and independent systems. A mobile phone (CEL) is used to remotely control the automatic measurements through the public GSM network. When available, however, a high speed internet connection can be fed to the Giga Ethernet switch of the instrument (Eth SW). This type of connection allows not only the monitoring, but also the transfer of some data for its remote analysis.

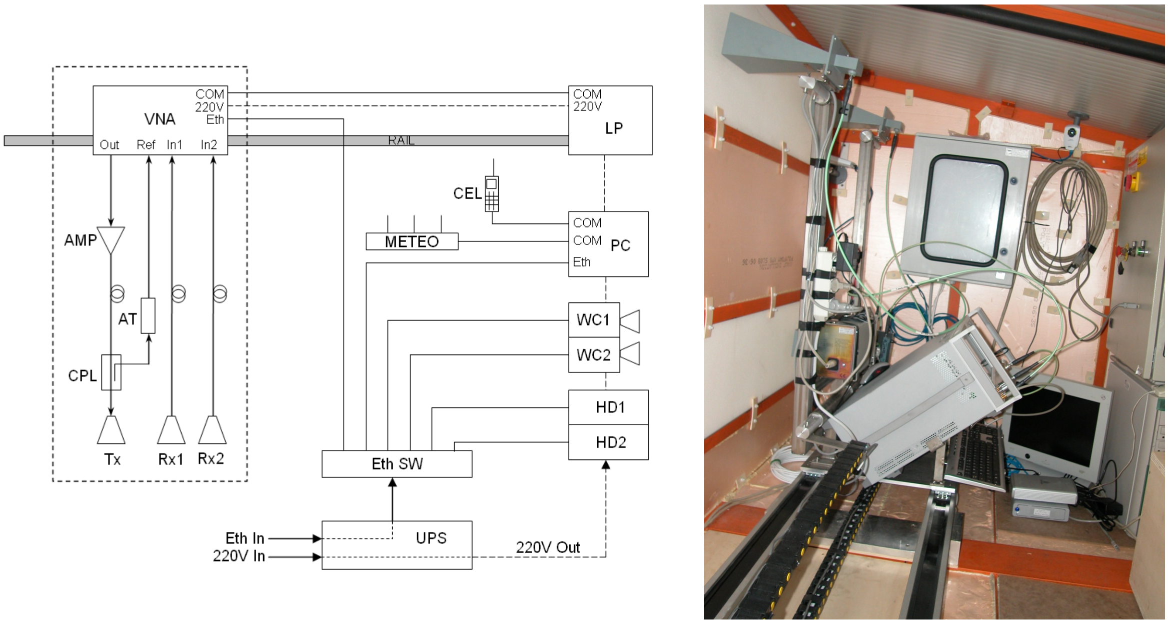

Figure 2: Schematic and components view of the LISA instrument

It is worth noting that the integration of all the radio-frequency components in the moving sled avoids folding the RF cables, a possible source of phase distortions in GB-SARs because of the continuous bending of the cables caused by the movement of the linear positioner.

The radar has been operated in vertical polarization at different frequencies through a linear aperture 1.9 m long, although the maximum aperture achievable by the system is limited by the rail length, which is 2.0 m. Regarding the band used and dynamic range, the system is limited by the characteristics of the network analyzer used:

- The network analyzer the first winter was an Agilent PNA E8358A, covering the band 300 kHz to 9 GHz and featuring a dynamic range of 113 dB.
- The network analyzer used the second winter was an Agilent PNA N5230A, covering the band 300 kHz to 13.5 GHz and featuring a dynamic range of 120 dB.

System parameters

The system parameters used during both winters are summarized in Table 1. Note that range (Δr) and cross-range ($\Delta\phi$) resolutions are computed according to the following equation:

$$\Delta r = \frac{c}{2BW}$$
$$\Delta\phi = \frac{\lambda_0 \cdot R}{2L} \tag{1}$$

The unambiguous range R_U, this is, the maximum range at which the system can create images free of aliases is defined in eq. (2):

$$R_U = \frac{c}{2\Delta f} = \frac{c}{2(BW / Nfre)} \quad (2)$$

Table 1: System parameters summary

	Winter 2005-2006	**Winter 2006-2007**
Radar		
Frequency span (GHz)	8.80 ... 8.92	13.15 ... 13.40
Frequency band, *BW* (MHz)	120	250
Frequency points, *Nfre*	1601	3201
Polarization	VV	VV
Power VNA (dBm)	5.0	4.0
Power amplifier (dB)	30	30
Linear aperture, *L* (m)	1.9	1.9
Aperture points, *LPpts*	231	231
Resolution		
Range resolution, Δr (m)	1.25	0.60
Cross-range resolution, $\Delta\phi$ (m)	10.2	6.83
Unambiguous range, R_U (m)	2001	1920
Acquisition rate (min/image)	9.93	11.56
Imaging		
Range distance, *R* (m)	750 ... 1550	750 ... 1550
Cross-range distance, ϕ (m)	–400 ... +400	–400 ... +400
Image size in range (pixel)	641	641
Image size in cross-range (pixel)	641	641

The Val d'Olen site at Alagna Valsesia

The LISA instrument was placed in the middle of a commercial ski resort (http://www.freerideparadise.it), located at Alagna Valsesia (Italy, Piedmont region) and managed by Monterosa 2000 S.p.A.

The system was located on the intermediate's stop concrete basement of the Funifor Pianalunga - Cimalegna - Passo Salati. Approximate coordinates of its location are: 45º 52' 22'' N, 7º 53' 48'' E, 2600 m of altitude. This place is locally known as Cimalegna. The location of the instrument is marked in Figure 3 with the box "LISA radar", while in semi-transparent red can be seen the area covered by the system.

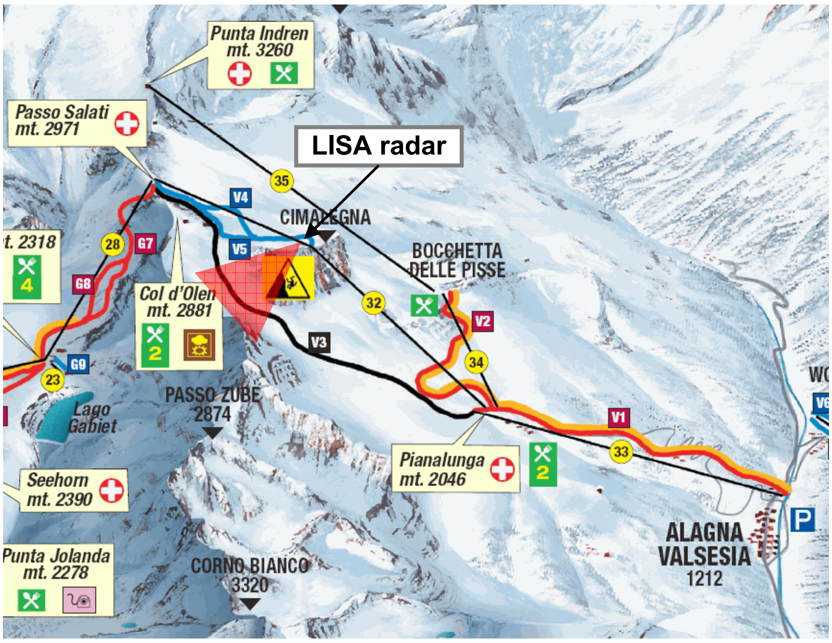

Figure 3: Map of the area with the radar field-of-view in red

The area monitored consists of a slope with 30 to 50 degrees of inclination, ranging from 2300 m to 2700 m a.s.l. The bottom part corresponds to the Olen valley (val d'Olen), where a ski track passes through (V3, black) putting under risk skiers when snow avalanches fall down. The instrument covered an area of nearly 800 m by 800 m, ranging approximately 750 m to 1550 m to the radar. Figure 3 shows the Alagna part of the ski map of the Monterosa complex. The Monterosa ski complex comprises currently three valleys, from West to East: Champoluc, Gressoney and Alagna.

Figures 4 and 5 show a couple of pictures of the Olen valley. The picture on Figure 4 has been taken from the radar position so it represents approximately the field-of-view of the instrument. Note that the ski track itself can not be seen from the radar position.

Figure 4: Picture of Val d'Olen from the radar position

The picture on Figure 5, instead, shows an artificially triggered avalanche on April the 5th, 2007 at the Olen valley. This avalanche was triggered as part of the regular maintenance of the ski resort the day after a big snow fall precipitated on the area. This kind of measures, activated before the opening of the ski resort, helps guarantee the security of skiers.

Figure 5: Picture of an artificially triggered avalanche at Val d'Olen

The field campaign

The objectives of the campaign can be summarized in the following points:

- Identification of structural changes in the snow cover such as mass movements or snow wetness anomalies.
- Estimation of the volume of snow displaced in natural or artificial avalanches.
- Identification of robust precursors in natural avalanches in order to provide an early warning.

To this aim, a field campaign of two winters has been carried out, giving a total of 195 days of data acquisition. Table 2 shows the intervals in which the LISA system monitored the Olen valley (*DataAlagna\FileList\flistOutCampaign.txt*). The first column (`####`) is a sequential number; `Day` represents the day number in the hydrological year (1 corresponds to the first of October, 93 corresponds to the first of January, etc); `Date` is the year, month and day of the measurements (YYYY/MM/DD); and `Time` (hh.mm) indicates the daily interval in which the measurements were carried out.

Table 2: Calendar of data acquisition by LISA

```
LISA monitor campaign
=================================================
####   Day   Date        Time
-------------------------------------------------
   1 : 177 : 2006/03/26  00.07h - 23.59h
   2 : 178 : 2006/03/27  00.08h - 23.56h
   3 : 179 : 2006/03/28  00.05h - 23.56h
   4 : 180 : 2006/03/29  00.06h - 23.59h
   5 : 181 : 2006/03/30  00.09h - 23.56h
   6 : 182 : 2006/03/31  00.05h - 23.54h
   7 : 183 : 2006/04/01  00.03h - 23.58h
   8 : 184 : 2006/04/02  00.08h - 23.54h
   9 : 185 : 2006/04/03  00.03h - 23.57h
  10 : 186 : 2006/04/04  00.07h - 23.56h
  11 : 187 : 2006/04/05  00.05h - 23.54h
  12 : 188 : 2006/04/06  00.04h - 23.53h
  13 : 189 : 2006/04/07  00.02h - 23.51h
  14 : 190 : 2006/04/08  00.00h - 23.58h
  15 : 191 : 2006/04/09  00.08h - 23.56h
  16 : 192 : 2006/04/10  00.06h - 23.54h
  17 : 193 : 2006/04/11  00.03h - 23.52h
  18 : 194 : 2006/04/12  00.01h - 23.50h
  19 : 195 : 2006/04/13  00.00h - 23.57h
  20 : 196 : 2006/04/14  00.06h - 23.55h
  21 : 197 : 2006/04/15  00.04h - 23.51h
  22 : 198 : 2006/04/16  00.01h - 23.58h
  23 : 199 : 2006/04/17  00.08h - 23.55h
  24 : 200 : 2006/04/18  00.04h - 23.58h
  25 : 201 : 2006/04/19  00.07h - 23.57h
  26 : 202 : 2006/04/20  00.06h - 23.56h
  27 : 203 : 2006/04/21  00.05h - 23.54h
  28 : 204 : 2006/04/22  00.03h - 23.52h
  29 : 205 : 2006/04/23  00.01h - 23.51h
  30 : 206 : 2006/04/24  00.00h - 23.58h
  31 : 207 : 2006/04/25  00.07h - 23.56h
  32 : 208 : 2006/04/26  00.05h - 23.54h
  33 : 209 : 2006/04/27  00.04h - 23.53h
  34 : 210 : 2006/04/28  00.02h - 23.50h
  35 : 211 : 2006/04/29  00.00h - 23.57h
  36 : 212 : 2006/04/30  00.07h - 23.56h
  37 : 213 : 2006/05/01  00.05h - 23.51h
  38 : 214 : 2006/05/02  00.00h - 23.56h
  39 : 215 : 2006/05/03  00.05h - 23.51h
  40 : 216 : 2006/05/04  00.00h - 23.55h
  41 : 217 : 2006/05/05  00.04h - 23.50h
  42 : 218 : 2006/05/06  00.00h - 23.58h
  43 : 219 : 2006/05/07  00.07h - 23.56h
  44 : 220 : 2006/05/08  00.05h - 23.54h
  45 : 221 : 2006/05/09  00.03h - 23.51h
  46 : 222 : 2006/05/10  00.00h - 23.58h
  47 : 223 : 2006/05/11  00.08h - 23.56h
  48 : 224 : 2006/05/12  00.05h - 23.53h
  49 : 225 : 2006/05/13  00.03h - 23.53h
  50 : 226 : 2006/05/14  00.02h - 23.51h
  51 : 227 : 2006/05/15  00.00h - 23.53h
  52 : 228 : 2006/05/16  00.03h - 23.53h
  53 : 229 : 2006/05/17  00.02h - 18.40h
  54 : 230 : 2006/05/18  13.26h - 23.55h
  55 : 231 : 2006/05/19  00.07h - 23.54h
  56 : 232 : 2006/05/20  00.06h - 23.52h
  57 : 233 : 2006/05/21  00.05h - 23.51h
  58 : 234 : 2006/05/22  00.03h - 23.59h
  59 : 235 : 2006/05/23  00.12h - 23.58h
  60 : 236 : 2006/05/24  00.10h - 23.56h
  61 : 237 : 2006/05/25  00.09h - 23.55h
  62 : 238 : 2006/05/26  00.08h - 23.54h
  63 : 239 : 2006/05/27  00.06h - 23.52h
  64 : 240 : 2006/05/28  00.04h - 23.50h
  65 : 241 : 2006/05/29  00.02h - 23.59h
  66 : 242 : 2006/05/30  00.12h - 23.54h
  67 : 243 : 2006/05/31  00.06h - 23.49h
  68 : 244 : 2006/06/01  00.01h - 23.52h
  69 : 245 : 2006/06/02  00.04h - 23.55h
  70 : 246 : 2006/06/03  00.07h - 23.58h
  71 : 247 : 2006/06/04  00.11h - 23.49h
  72 : 248 : 2006/06/05  00.01h - 23.52h
  73 : 249 : 2006/06/06  00.05h - 09.12h
  74 :  52 : 2006/11/21  12.59h - 23.55h
  75 :  53 : 2006/11/22  00.01h - 23.54h
  76 :  54 : 2006/11/23  00.01h - 23.53h
  77 :  55 : 2006/11/24  00.00h - 23.56h
  78 :  56 : 2006/11/25  00.03h - 23.54h
  79 :  57 : 2006/11/26  00.01h - 23.53h
  80 :  58 : 2006/11/27  00.00h - 13.54h
  81 :  59 : 2006/11/28  15.31h - 23.54h
  82 :  60 : 2006/11/29  00.00h - 23.59h
  83 :  61 : 2006/11/30  00.06h - 23.59h
  84 :  62 : 2006/12/01  00.06h - 13.58h
  85 :  65 : 2006/12/04  17.31h - 23.59h
  86 :  66 : 2006/12/05  00.05h - 23.55h
  87 :  67 : 2006/12/06  00.02h - 23.59h
  88 :  68 : 2006/12/07  00.05h - 23.56h
  89 :  69 : 2006/12/08  00.03h - 23.56h
  90 :  70 : 2006/12/09  00.03h - 23.54h
  91 :  71 : 2006/12/10  00.00h - 23.55h
  92 :  72 : 2006/12/11  00.02h - 23.54h
  93 :  73 : 2006/12/12  00.01h - 23.54h
  94 :  74 : 2006/12/13  00.00h - 14.11h
  95 :  75 : 2006/12/14  10.37h - 13.34h
  96 :  76 : 2006/12/15  09.27h - 14.12h
  97 :  77 : 2006/12/16  09.51h - 23.54h
  98 :  78 : 2006/12/17  00.01h - 23.56h
```

99	79	2006/12/18	00.02h - 23.57h
100	80	2006/12/19	00.03h - 23.57h
101	81	2006/12/20	00.04h - 23.53h
102	82	2006/12/21	00.00h - 23.55h
103	83	2006/12/22	00.01h - 23.58h
104	84	2006/12/23	00.05h - 23.56h
105	85	2006/12/24	00.03h - 14.56h
106	89	2006/12/28	10.43h - 23.57h
107	90	2006/12/29	00.03h - 15.05h
108	91	2006/12/30	14.00h - 23.57h
109	92	2006/12/31	00.03h - 23.58h
110	93	2007/01/01	00.05h - 23.54h
111	94	2007/01/02	00.01h - 23.56h
112	95	2007/01/03	00.03h - 23.55h
113	96	2007/01/04	00.02h - 15.43h
114	102	2007/01/10	00.09h - 23.53h
115	103	2007/01/11	00.03h - 23.53h
116	104	2007/01/12	00.03h - 09.09h
117	108	2007/01/16	00.08h - 23.58h
118	109	2007/01/17	00.11h - 23.57h
119	110	2007/01/18	00.10h - 23.59h
120	111	2007/01/19	00.11h - 23.59h
121	112	2007/01/20	00.12h - 23.47h
122	113	2007/01/21	00.00h - 23.47h
123	114	2007/01/22	00.00h - 23.59h
124	115	2007/01/23	00.12h - 23.47h
125	116	2007/01/24	00.00h - 23.47h
126	117	2007/01/25	00.00h - 23.48h
127	118	2007/01/26	00.00h - 23.59h
128	119	2007/01/27	00.12h - 23.59h
129	120	2007/01/28	00.11h - 23.59h
130	121	2007/01/29	00.12h - 23.48h
131	122	2007/01/30	00.00h - 23.49h
132	123	2007/01/31	00.02h - 23.50h
133	124	2007/02/01	00.03h - 23.51h
134	125	2007/02/02	00.03h - 23.51h
135	126	2007/02/03	00.04h - 23.51h
136	127	2007/02/04	00.04h - 23.52h
137	128	2007/02/05	00.05h - 23.58h
138	129	2007/02/06	00.11h - 23.48h
139	130	2007/02/07	00.00h - 23.48h
140	131	2007/02/08	00.01h - 23.49h
141	132	2007/02/09	00.02h - 23.59h
142	133	2007/02/10	00.12h - 23.48h
143	134	2007/02/11	00.00h - 23.49h
144	135	2007/02/12	00.02h - 23.51h
145	136	2007/02/13	00.04h - 23.53h
146	137	2007/02/14	00.05h - 23.56h
147	138	2007/02/15	00.09h - 23.59h
148	139	2007/02/16	00.12h - 23.49h
149	140	2007/02/17	00.02h - 23.52h
150	141	2007/02/18	00.05h - 23.55h
151	142	2007/02/19	00.08h - 23.59h
152	143	2007/02/20	00.12h - 23.50h
153	144	2007/02/21	00.03h - 23.53h
154	145	2007/02/22	00.06h - 23.57h
155	146	2007/02/23	00.10h - 23.49h
156	147	2007/02/24	00.02h - 23.53h
157	148	2007/02/25	00.06h - 23.57h
158	149	2007/02/26	00.09h - 23.48h
159	150	2007/02/27	00.01h - 23.52h
160	151	2007/02/28	00.05h - 23.55h
161	152	2007/03/01	00.08h - 23.58h
162	153	2007/03/02	00.10h - 23.49h
163	154	2007/03/03	00.02h - 23.47h
164	155	2007/03/04	00.00h - 23.47h
165	156	2007/03/05	00.01h - 23.57h
166	157	2007/03/06	00.09h - 23.48h
167	158	2007/03/07	00.01h - 23.51h
168	159	2007/03/08	00.04h - 23.54h
169	160	2007/03/09	00.06h - 23.55h
170	161	2007/03/10	00.08h - 23.57h
171	162	2007/03/11	00.10h - 23.59h
172	163	2007/03/12	00.12h - 23.49h
173	164	2007/03/13	00.02h - 23.52h
174	165	2007/03/14	00.05h - 23.55h
175	166	2007/03/15	00.07h - 23.58h
176	167	2007/03/16	00.11h - 23.49h
177	168	2007/03/17	00.01h - 23.51h
178	169	2007/03/18	00.04h - 23.55h
179	170	2007/03/19	00.07h - 23.47h
180	171	2007/03/20	00.00h - 23.50h
181	172	2007/03/21	00.03h - 23.53h
182	173	2007/03/22	00.05h - 23.56h
183	174	2007/03/23	00.09h - 23.59h
184	175	2007/03/24	00.12h - 23.50h
185	176	2007/03/25	00.03h - 23.50h
186	177	2007/03/26	00.03h - 23.53h
187	178	2007/03/27	00.06h - 23.56h
188	179	2007/03/28	00.09h - 23.59h
189	180	2007/03/29	00.11h - 23.47h
190	181	2007/03/30	00.00h - 23.50h
191	182	2007/03/31	00.03h - 23.52h
192	183	2007/04/01	00.05h - 23.55h
193	184	2007/04/02	00.08h - 23.58h
194	185	2007/04/03	00.10h - 23.47h
195	186	2007/04/04	00.00h - 07.53h

Figure 6 shows in a compact way the days in which the LISA system monitored the test site and also the days in which avalanches were detected by the LISA instrument.

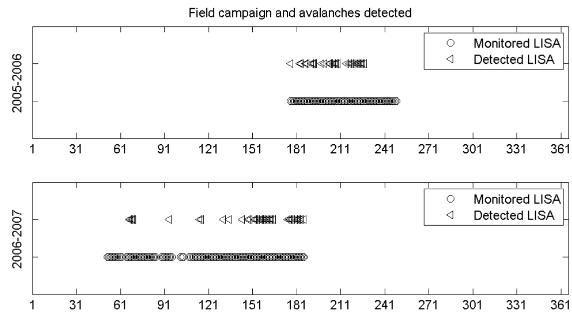

Figure 6: Days of data acquisition (in the hydrological year) and avalanches detected

It is worth noting that another campaign is foreseen for the winter 2007 – 2008 with the same instrument in the same location. That campaign, however, will have a different objective: the set up of an automatic system for the identification and classification of possible avalanche events. Technical personnel from the ski resort will evaluate the usefulness of that system in the daily maintenance operations of the ski resort.

Data collection

Two kinds of data products have been acquired from the LISA instrument: visual imagery and radar imagery.

Concerning the visual imagery, a digital camera with resolution 640x480 pixels has been taking pictures of the LISA field-of-view day and night every 15 minutes.

Regarding the radar imagery, the instrument has been operated with the parameters shown in Table 1. The raw data has been focused in a 641x641 pixels image over an 800x800 m rectangle by means of an in-house near-field FFT-based algorithm.

The system has operated during these two winter campaigns with one antenna in transmission and two antennas in reception vertically separated 80.5 cm. That two antenna configuration adds stereoscopy to the instrument, allowing the topographic working mode of the system. This mode is used, as will be shown later on, to generate digital elevation maps (DEM) of the field-of-view.

In addition, meteorological data is available from the Istituto Mosso automatic station. This meteorological station is situated at Passo dei Salati (2900 m a.s.l.), approximately one kilometre far away from the LISA instrument and managed by Comando Truppe Alpine - Servizio Meteomont.

Data archive

Concerning the visual imagery, a total of 18792 pictures are available from 2006/07/19 to 2007/04/04 (195 days approximately) in JPEG format. This archive occupies 600 MB and is available on the DVD at *DataAlagna\datacamo*.

The radar raw data contains a total of 114.107 files, from 2006/03/26 to 2007/04/04 (195 days). This archive occupies 240 GB. The acquisition rate is specified in Table 1, and is approximately 10 min per image during both winters. Note that each acquisition consists of 4 files, 2 corresponding to one receiving antenna, and 2 corresponding to the other receiving antenna. From these 2 files in each case, one corresponds to the raw data itself while the other contains the acquisition parameters.

The first product directly derived from the radar raw data is the imaged (also called focused) data. Figure 7 shows a schematic of the data flow of the LISA instrument.

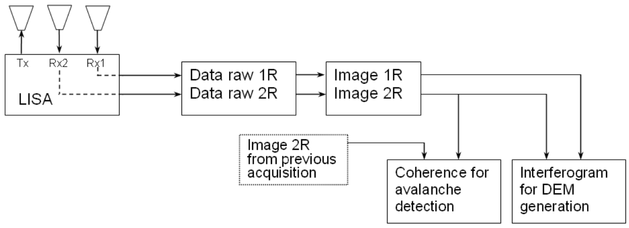

Figure 7: Data flow of the data generated by the radar system

A total of 108.586 focused images are available for the same period as the raw data. This archive occupies 166 GB. As with the raw data, each acquisition generates 4 image files: 2 corresponding to one receiving antenna, and 2 corresponding to the other receiving antenna.

From these 2 files in each case, one corresponds to the image itself while the other contains the focusing parameters.

From the imaged data two products have been obtained: double-pass interferograms with temporal baseline (10 min), and single-pass interferograms with spatial baseline (80.5 cm).

Double-pass interferograms are computed with one of the receiving antennas and the data corresponding to two consecutive acquisitions. The absolute value of the interferograms, or coherence, has been used to identify avalanches during the campaign.

Single-pass interferograms are computed with the data of the two receiving antennas acquired at the same instant of time. The phase of the interferograms, or interferometric phase, has been used to compute the DEMs of the instrument's field-of-view.

Concerning the coherence maps for avalanche detection, a total of 27.143 files are available for the same period as the focused data, occupying 3 GB. Note that coherence maps have only been computed for one of the receiving antennas, since the coherence maps generated with the second one are identical to the firsts. TIFF images of the absolute value of the complex coherence are available on the DVD at *DataAlagna\DataProcessed\Coherence_01.*

In addition, the images of the absolute value of the complex coherence corresponding to the natural and artificial avalanches monitored are copied in an independent folder for an easier browsing. In particular, each avalanche can be seen in two different ways:

- Two-dimensional radar images in the coordinates-frame of the instrument, in TIFF format (*DataAlagna\DataProcessed\Avalanches*).
- Three-dimensional coherence images in PPM format (*3DVisor\PPM_3DVisor*). These files can be viewed in 2D by any image viewer supporting the PPM format, or can opened with specific vision software (*3DVisor\RadarDem[v2.0-1a].exe*) and overlapped to a DEM generated with the LISA instrument (*3DVisor\AlagnaCML-dem20067.dem*), offering the possibility to pan, tilt and zoom the scene to better appreciate the avalanche paths in three dimensions.

In the folder *3DVisor\PPM_3DVisor\Skiers* some images showing the tracks of several skiers passing by the radar field-of-view can be found. They are characterized by a loose in coherence as avalanches, but with a horizontal direction instead of the vertical one of avalanches.

Concerning the interferograms for DEM generation, no massive products have been generated. Instead, some DEMs have created at specific days with the particular interest of retrieving the snow volume displaced during avalanches. The results derived from the topographic mode of the instrument can be found at *DataAlagna\DataProcessed\MapsDEM*.

Data visualization

The huge amount of data generated by the system is fully managed by a software tool internally developed at the JRC of Ispra. A screenshot of this software can be seen on Figure 8.

This software is installed on the headquarters of Monterosa 2000 S.p.A. at Alagna, where the technical personnel can access in real-time the radar data. The fast algorithm implemented for the data processing and the wireless network connection (12 Mbps) between the instrument and the offices allows the visualization of every image acquired by LISA just a few seconds after the acquisition is completed.

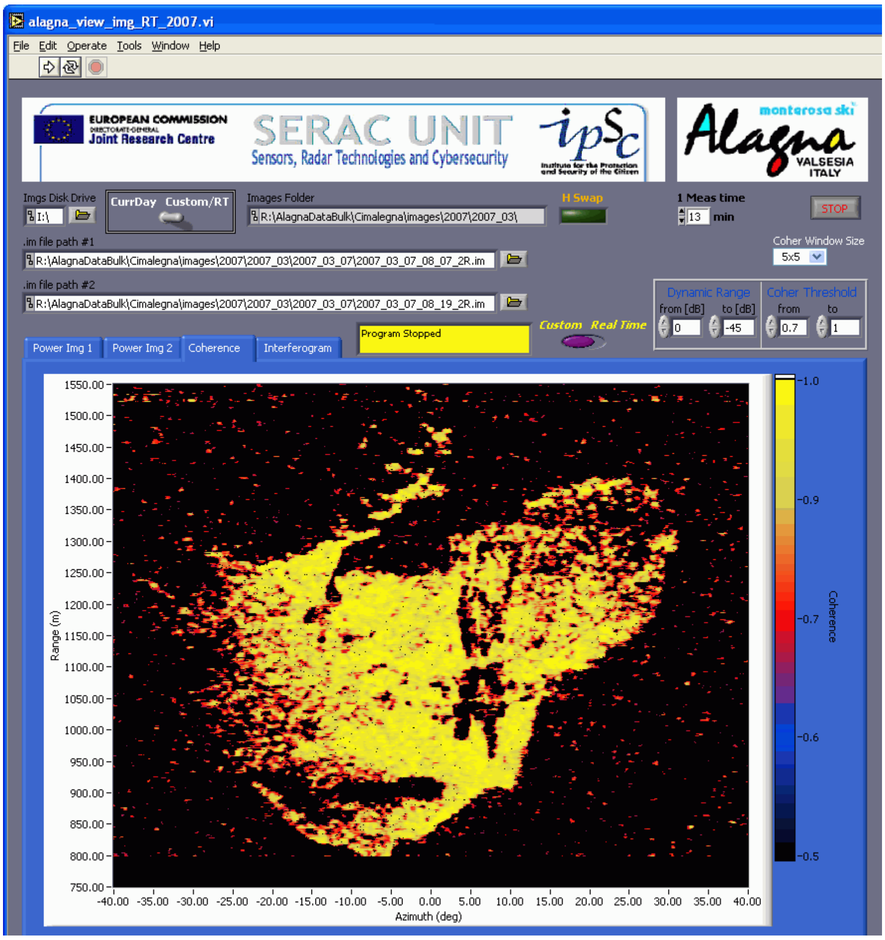

Figure 8: In-house software for the real-time radar data visualization

Two working modes are defined: real-time visualization of images as they are generated by the radar, or historic images browsing when there is the need to check the imagery produced at a certain instant of time. This last mode becomes particularly interesting during the hours before the public aperture of the ski resort: the personnel in charge of the security in the slopes can easily check the avalanche activity or bad weather produced during the night before and consequently take the necessary actions to minimize the risk of skiers and free-riders.

This tool behaves, thus, as a radar camera with a refresh rate of approximately 1 image every 10 minutes, with day and night visibility and even providing useful images under bad weather conditions. It is in practice a perfect complement to the visual cameras already installed in the ski resort for its management and operation.

Results

Different types of results have been derived from the data acquired during the two years campaign. It is worth noting that the nature of the system used allows the coverage of a local but wide area (800m x 800m) with a pixel resolution of approximately 1m x 8m. The radar works perfectly well during day and night hours, and it assures a good performance even under bad weather conditions (rain fall, snow fall, fog, etc.). These characteristics overcome the techniques classically used for the continuous monitoring of the snow cover: optical imagery and networks of geophones.

Avalanche monitoring

Thanks to the automatic and continuous measurements performed a huge number of natural avalanches have been monitored, as well as some artificially triggered. A catalogue has been created containing the date and time of the avalanches, their size and the coordinates of the starting point according to the grid shown in Figure 9.

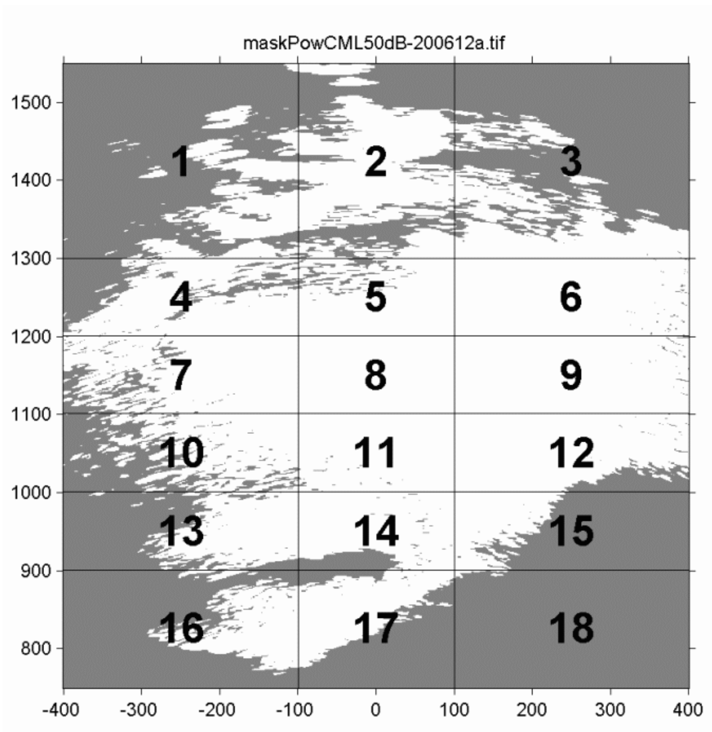

Figure 9: Grid of the LISA field-of-view in 18 positions

Table 3 shows the list of artificial avalanches, to the knowledge of the authors, monitored by the LISA system at Alagna. The column `Pos` indicates the position of the starting point of the avalanche according to Figure 9, `Axis` indicates the horizontal x vertical dimensions in meters of the avalanche affected zone, and `Area` is the area in square meters of the avalanche path (the table is also available at *DataAlagna\FileList\flistLISAdetect-artif.txt*). Finally, the last column `Mn` indicates with an asterisk '*' avalanches manually classified, this is, avalanches not automatically identified by the classification algorithm.

Table 3: Artificial avalanches monitored

%Date	Time	Pos	Axis	Area	Mn
2007/03/08	08.34h	5	200x325	40500	
2007/03/08	08.47h	4	100x150	15000	*

Figures 10 and 11 show the absolute value of the complex coherence of a sequence of 4 images in which the artificial avalanches where triggered.

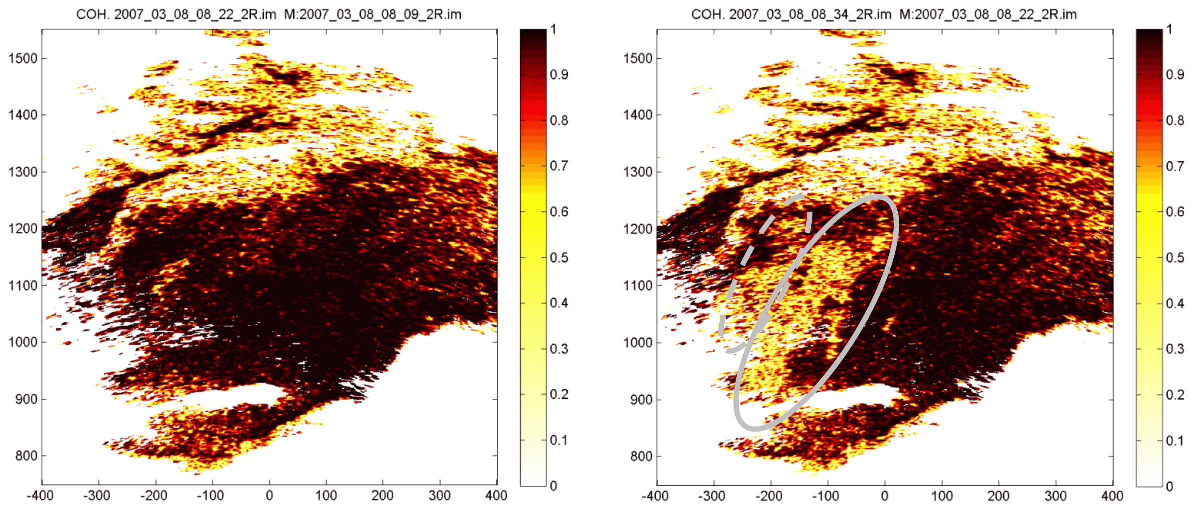

Figure 10: Artificial avalanches (marked gray) seen by LISA

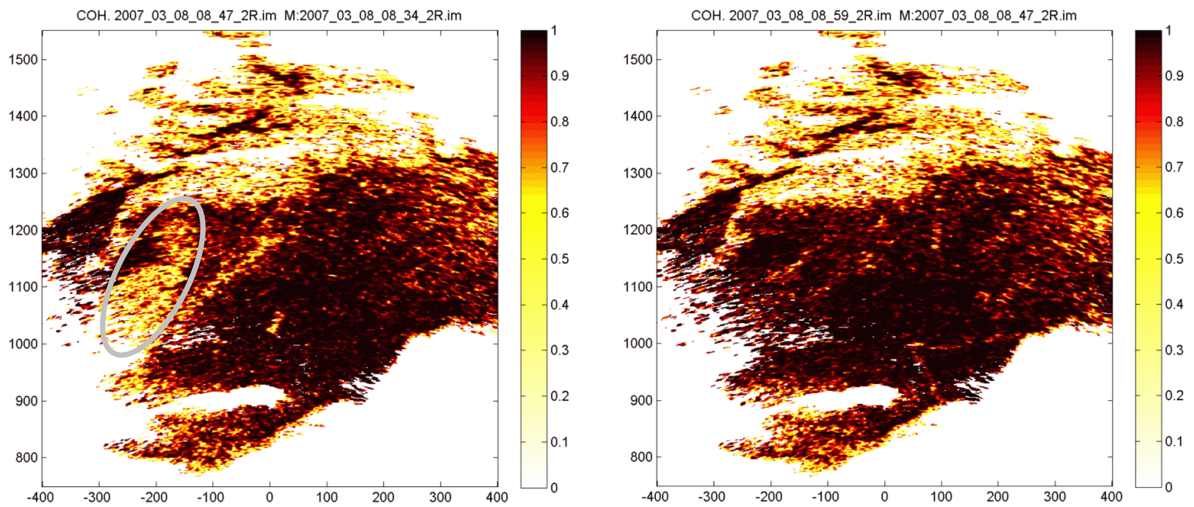

Figure 11: Artificial avalanches (marked gray) seen by LISA

Exact instants of time can be seen on top of the images, and are:

- 2007/03/08 08.22h Stable situation
- 2007/03/08 08.34h First avalanche triggered
- 2007/03/08 08.47h Second avalanche triggered
- 2007/03/08 08.59h Stable situation

The avalanches produce a clear reduction of the absolute value of the coherence on the affected paths, decreasing the average value from 0.95 to 0.50. The interferometric phase, although not shown here, becomes completely random on the avalanche paths. These patterns allow a feasible automatic detection and classification based on brightness binarization and contour detection.

The absolute value of the complex coherence ranges from zero to one, where zero indicates a complete lose of coherence (the scene has changed dramatically from one image to another) and one indicates that only small changes of the phase may have occurred (the scene is almost identical to the previous one). Since a full image acquisition takes 10 minutes, all instabilities happening in that period are integrated into the radar image. This is why in the image at 8.34h (Figure 10) apart of the avalanche marked with a continuous gray oval, the avalanche clearly appearing at 8.47h (Figure 11) can also be slightly appreciated. That second avalanche has been marked with a dashed gray oval in the 8.34h image.

Note on the titles of the images the day and time of the data used for the computation of the complex coherence (interferogram). COH states the image for which the interferograms is computed, M is the image name of the previous acquisition and 2R indicates that the second antenna in reception is being used. Dates are formatted YYYY_MM_DD_hh_mm. Concerning the axes, the figures use a local coordinate frame centred on the LISA instrument. The horizontal axis represents the azimuth in meters while the vertical one represents the range also in meters.

In a similar way to the previous table, Tables 4 and 5 show the list of avalanches monitored by the LISA system during the campaign. This list is available at *DataAlagna\FileList\flistOutAvalanche.txt*. The last column, `Mn`, indicates with an asterisk '*' or sum sign '+' avalanches manually added, this is, avalanches not automatically identified by the classification algorithm. Asterisk '*' is used for avalanches not occurring close in time to other avalanches properly identified by the algorithm, while the sum sign '+' is used for avalanches happening close in time to other properly identified.

The distinction between avalanches not automatically classified but being far or close to other automatically identified is done because in periods of high avalanche activity it may happen that the algorithm misses some of the simultaneous and consecutive avalanches. The avalanches missed, when being close in time to other properly identified, are of minor importance since other avalanches may have been properly identified and allow the operator to know the overall avalanche activity.

Table 4: Avalanches monitored, winter 2005-2006

Date	Time	Pos	Axis	Area	Mn
2006/03/26	09.44h	7	25x150	4050	
2006/03/26	10.20h	8	100x300	13500	
2006/03/26	10.38h	5	25x250	7700	
2006/03/26	10.47h	2	50x475	10850	
2006/03/26	11.23h	11	25x100	2300	
2006/04/01	15.26h	8	25x175	3050	
2006/04/01	15.44h	5	25x75	1800	
2006/04/01	16.39h	6	100x300	30000	*
2006/04/01	20.18h	6	25x75	2400	
2006/04/02	04.43h	3	25x100	1900	
2006/04/05	02.10h	5	50x250	12500	*
2006/04/05	02.27h	6	50x250	12500	*
2006/04/05	03.30h	9	25x125	2200	
2006/04/05	05.35h	8	25x75	2100	*
2006/04/05	06.02h	5	50x250	12500	+
2006/04/05	06.11h	3	50x275	9900	
2006/04/05	06.20h	10	25x75	2450	
2006/04/05	06.29h	6	25x175	3450	
2006/04/05	06.56h	2	125x375	37200	
2006/04/05	06.56h	3	50x200	8100	
2006/04/05	06.56h	3	75x375	9600	
2006/04/05	07.14h	5	50x325	10200	
2006/04/05	07.32h	6	50x200	10000	+
2006/04/05	07.41h	3	50x225	9050	
2006/04/05	07.50h	8	50x125	6000	
2006/04/05	07.59h	9	25x175	5300	
2006/04/05	08.08h	5	50x150	7500	+
2006/04/05	08.35h	3	175x375	42850	
2006/04/05	09.02h	5	25x225	5850	
2006/04/05	09.57h	11	25x100	2750	
2006/04/05	10.15h	6	25x100	2750	
2006/04/05	12.04h	11	25x100	3450	
2006/04/05	14.39h	9	25x125	3500	
2006/04/05	14.58h	3	25x150	4300	
2006/04/05	15.16h	5	25x200	5100	
2006/04/05	15.34h	9	25x150	4150	

2006/04/05	16.02h	3	25x150	4350	
2006/04/06	10.22h	5	50x200	10000	*
2006/04/09	12.43h	5	25x200	4400	
2006/04/09	13.01h	5	25x250	5700	
2006/04/09	13.01h	5	25x75	2500	
2006/04/10	10.52h	6	50x200	10000	*
2006/04/10	11.37h	6	25x100	2700	
2006/04/10	12.04h	6	150x200	30000	*
2006/04/10	12.22h	5	100x250	15500	
2006/04/10	13.53h	6	25x100	3000	
2006/04/10	14.03h	6	50x300	15000	+
2006/04/10	14.12h	3	50x275	11100	
2006/04/10	14.12h	3	75x200	9900	
2006/04/10	14.21h	3	100x300	17550	
2006/04/10	15.07h	11	50x100	3800	
2006/04/10	15.52h	8	50x150	7850	
2006/04/11	00.03h	3	75x225	16200	
2006/04/11	05.34h	2	200x375	45300	
2006/04/16	08.13h	7	25x50	1600	
2006/04/16	08.22h	7	25x200	4600	
2006/04/16	08.49h	5	50x150	7500	*
2006/04/16	09.34h	7	25x100	2700	
2006/04/16	10.19h	6	25x150	2850	
2006/04/16	10.19h	6	25x75	2000	
2006/04/16	11.14h	3	25x100	2400	
2006/04/18	00.30h	3	75x250	12800	
2006/04/18	12.44h	11	25x125	3100	
2006/04/18	13.20h	11	25x100	3500	
2006/04/21	12.30h	8	25x100	3150	
2006/04/21	12.30h	5	25x75	2000	
2006/04/21	13.07h	5	50x100	5000	*
2006/04/22	17.13h	6	25x250	5800	
2006/04/22	17.13h	5	25x75	1800	
2006/04/22	17.31h	6	50x250	12500	*
2006/04/24	13.20h	3	25x200	4650	
2006/04/24	13.29h	3	50x125	5350	
2006/04/24	17.09h	5	25x100	2500	
2006/04/24	17.09h	4	50x100	3500	
2006/04/24	19.19h	4	25x75	2650	
2006/04/25	01.18h	3	25x175	3550	
2006/04/25	01.36h	3	50x300	15000	*
2006/04/25	01.45h	3	50x200	10000	*
2006/04/25	16.03h	5	75x375	13450	
2006/04/25	16.12h	6	25x150	2200	
2006/04/25	16.31h	5	25x325	7950	
2006/04/25	16.40h	4	25x225	5800	
2006/04/26	14.30h	5	25x100	3500	
2006/04/26	15.43h	8	25x125	2700	
2006/04/27	11.44h	5	25x125	3200	
2006/04/27	13.51h	4	25x50	1800	
2006/04/27	14.28h	4	25x75	2500	
2006/04/27	14.46h	5	25x125	3100	
2006/05/03	14.24h	5	25x150	3750	*
2006/05/03	14.51h	8	25x225	4450	
2006/05/05	12.44h	8	25x225	4950	
2006/05/06	11.40h	8	50x175	5900	
2006/05/06	12.16h	8	25x175	3500	
2006/05/06	15.01h	8	50x150	4800	
2006/05/06	18.32h	8	50x275	10450	
2006/05/07	09.31h	5	25x75	3150	
2006/05/07	09.58h	4	25x75	1750	
2006/05/07	10.07h	6	25x125	2600	
2006/05/07	10.17h	5	100x150	15000	+
2006/05/07	11.38h	6	50x250	12500	+
2006/05/07	11.47h	8	25x175	3500	
2006/05/07	11.56h	11	50x100	5000	+
2006/05/07	12.42h	8	25x250	6350	
2006/05/07	13.09h	5	25x225	5100	
2006/05/07	13.27h	5	50x250	12500	*
2006/05/07	14.04h	4	50x150	7500	*
2006/05/07	14.59h	4	50x150	7500	+
2006/05/07	15.08h	8	25x100	2700	
2006/05/07	15.17h	11	50x125	3350	
2006/05/09	00.48h	3	175x300	37300	*
2006/05/09	00.56h	3	200x450	61150	*
2006/05/09	01.14h	5	50x250	7500	*
2006/05/09	01.23h	3	175x500	37800	*
2006/05/09	01.23h	3	50x250	13450	*
2006/05/09	01.32h	2	100x500	28500	*
2006/05/09	01.41h	5	125x300	26100	*
2006/05/09	09.00h	9	100x250	17800	*
2006/05/10	21.57h	3	150x250	37500	*
2006/05/10	22.25h	8	100x200	12550	
2006/05/11	07.25h	7	75x125	4900	
2006/05/11	07.34h	6	100x325	16200	
2006/05/11	07.52h	5	175x250	25850	
2006/05/11	09.50h	6	175x325	35700	*
2006/05/11	10.53h	3	75x375	25200	
2006/05/11	11.11h	6	50x150	5750	
2006/05/12	10.24h	3	50x225	9100	
2006/05/12	10.51h	3	150x250	19550	
2006/05/12	13.16h	9	25x100	2100	
2006/05/12	14.38h	8	25x150	1750	
2006/05/12	14.38h	5	25x125	1900	
2006/05/12	14.48h	4	25x100	3750	
2006/05/12	15.15h	5	50x150	7500	*
2006/05/12	15.52h	5	50x100	5000	*
2006/05/13	10.04h	5	50x125	4950	
2006/05/13	12.02h	7	25x100	2100	
2006/05/13	14.37h	3	25x150	2400	
2006/05/13	14.46h	3	25x100	2650	
2006/05/14	12.46h	5	50x200	10000	*
2006/05/15	09.51h	5	25x50	1900	
2006/05/15	23.06h	4	150x150	12400	

Table 5: Avalanches monitored, winter 2006-2007

Date	Time	Pos	Axis	Area	Mn
2006/12/06	11.56h	9	25x125	2300	
2006/12/06	12.09h	6	50x100	5000	*
2006/12/06	13.02h	5	50x100	5000	*
2006/12/06	13.27h	6	50x150	7500	*
2006/12/06	20.27h	5	50x100	5000	*
2006/12/06	21.52h	11	50x100	5000	*
2006/12/07	00.05h	6	50x225	10450	
2006/12/07	00.05h	6	50x225	7600	
2006/12/07	00.11h	6	50x250	10500	
2006/12/07	11.22h	9	25x100	3400	
2006/12/07	12.06h	9	25x100	2400	
2006/12/08	15.46h	6	75x250	18750	*
2006/12/08	15.53h	5	100x250	25000	*
2006/12/08	15.59h	6	150x300	45000	*
2006/12/08	16.12h	11	25x100	3650	
2006/12/08	16.25h	6	75x250	12600	
2006/12/08	16.31h	6	100x200	20000	+
2006/12/08	17.16h	8	50x125	3650	
2006/12/08	17.55h	4	200x250	50000	*
2006/12/08	18.14h	6	100x200	20000	*
2006/12/08	18.33h	6	50x200	10000	*
2006/12/08	18.46h	2	50x350	17500	*
2006/12/08	19.00h	6	50x125	6500	
2006/12/08	19.00h	6	25x225	4850	
2006/12/08	19.26h	6	50x75	2150	
2006/12/08	19.52h	3	100x400	29350	
2006/12/08	20.05h	9	25x200	4700	
2006/12/08	20.38h	6	100x300	25450	
2006/12/08	20.38h	7	50x75	4400	
2006/12/08	20.38h	11	25x100	4050	
2006/12/08	20.51h	6	100x250	15400	
2006/12/08	21.17h	7	125x225	18600	
2006/12/08	21.24h	3	150x400	32600	
2006/12/08	22.03h	7	25x50	2100	
2006/12/08	22.10h	6	50x275	12400	
2006/12/08	22.17h	6	100x275	15950	
2006/12/08	22.17h	7	100x200	13800	
2006/12/08	22.23h	6	100x300	19900	
2006/12/08	22.36h	5	50x250	12500	*
2006/12/08	23.03h	3	25x250	5750	
2006/12/08	23.10h	3	25x250	5800	+
2006/12/08	23.43h	6	125x325	27350	
2006/12/08	23.43h	5	100x325	16550	
2006/12/08	23.50h	6	50x200	10000	+
2006/12/09	00.03h	4	75x175	12550	
2006/12/09	00.15h	11	25x50	1650	
2006/12/09	01.20h	5	50x250	7650	
2006/12/09	02.19h	6	25x175	5550	
2006/12/09	06.01h	8	25x100	2650	
2006/12/09	06.19h	6	125x200	17600	
2007/01/02	19.01h	9	50x100	2800	
2007/01/23	08.22h	11	25x50	1550	

2007/01/23	08.35h	6	25x225	7700	
2007/01/23	08.35h	11	25x125	2550	
2007/01/23	08.47h	11	50x100	4750	
2007/01/23	09.13h	6	125x275	14850	
2007/01/23	09.13h	3	25x100	3200	
2007/01/23	09.25h	6	50x350	13800	
2007/01/23	09.38h	11	25x75	1550	
2007/01/23	09.50h	11	25x100	2350	
2007/01/23	10.03h	6	50x100	5000	*
2007/01/23	13.25h	6	50x225	9550	
2007/01/23	13.25h	6	25x250	6100	
2007/01/23	13.25h	5	25x200	4250	
2007/01/23	13.38h	9	75x175	6650	
2007/01/23	14.16h	3	150x250	21150	
2007/01/23	14.41h	3	275x350	54150	
2007/01/23	14.54h	3	150x275	31100	*
2007/01/23	15.31h	3	275x450	85100	
2007/01/23	15.31h	7	25x75	1850	
2007/01/23	15.57h	8	50x100	5000	*
2007/01/23	16.09h	5	50x100	5000	*
2007/01/24	01.02h	3	75x300	10600	
2007/01/24	01.15h	5	50x150	7500	*
2007/01/24	01.27h	6	50x200	10000	*
2007/01/24	01.40h	6	100x200	20000	*
2007/01/24	01.52h	5	50x100	5000	*
2007/01/24	02.55h	6	50x150	7500	*
2007/01/24	03.08h	8	50x100	5000	*
2007/01/24	03.20h	5	50x150	7500	*
2007/01/24	03.33h	5	50x150	7500	+
2007/01/24	03.45h	4	25x75	1600	
2007/01/24	03.58h	4	25x50	1850	*
2007/01/24	04.23h	5	25x150	3750	*
2007/01/24	05.38h	6	200x325	34050	
2007/01/24	05.38h	8	25x75	1900	
2007/01/24	05.51h	3	50x100	4700	
2007/01/24	06.04h	11	25x75	2600	
2007/01/24	06.29h	6	50x100	5000	*
2007/01/24	06.54h	3	100x300	13200	
2007/01/24	16.35h	3	25x400	10000	*

2007/02/08	15.21h	15	25x75	2200	
2007/02/12	12.17h	12	25x75	2750	
2007/02/12	12.30h	9	25x225	3200	
2007/02/21	12.07h	14	25x50	1450	
2007/02/21	13.47h	11	25x100	2250	
2007/02/25	13.01h	9	50x100	5000	*
2007/02/25	13.13h	6	75x250	11500	*
2007/02/26	13.42h	13	25x50	1900	
2007/02/26	17.03h	11	25x75	2000	

2007/03/01	18.41h	7	25x50	1650	
2007/03/01	21.00h	9	25x225	6050	
2007/03/01	21.38h	9	50x100	5000	*
2007/03/02	01.00h	6	50x325	8400	
2007/03/02	01.13h	3	25x325	5300	
2007/03/02	01.37h	7	50x100	5000	*
2007/03/02	03.42h	3	175x400	35300	
2007/03/02	07.39h	3	150x400	42350	
2007/03/02	08.04h	7	25x75	2550	*
2007/03/02	14.21h	11	50x100	5000	*
2007/03/03	06.15h	9	25x175	4200	
2007/03/03	06.53h	6	75x225	8700	
2007/03/03	07.18h	11	25x75	2750	
2007/03/05	15.32h	11	50x125	5300	
2007/03/06	22.57h	9	25x125	2150	
2007/03/07	02.43h	6	50x200	10000	*
2007/03/07	03.08h	6	200x300	60000	*
2007/03/07	03.32h	3	125x350	31800	
2007/03/07	04.22h	5	50x350	10400	
2007/03/07	06.14h	9	50x175	8200	
2007/03/07	06.14h	9	25x100	2400	
2007/03/07	06.27h	3	25x100	2550	
2007/03/07	06.52h	6	100x225	22500	*
2007/03/07	07.04h	6	75x225	15550	
2007/03/07	07.17h	5	50x150	7500	*
2007/03/07	07.29h	3	75x325	13000	
2007/03/07	08.07h	4	75x175	8450	
2007/03/07	08.19h	6	100x225	22500	
2007/03/07	08.32h	6	50x150	7500	*
2007/03/07	08.57h	6	150x275	22750	
2007/03/07	08.57h	2	75x375	18800	
2007/03/07	09.34h	6	75x200	15000	*
2007/03/07	11.40h	11	50x150	7500	*
2007/03/07	12.55h	8	75x200	13350	
2007/03/07	14.36h	12	25x100	1800	
2007/03/07	16.03h	6	50x200	8900	

2007/03/07	16.16h	6	75x300	13850	
2007/03/07	16.29h	6	50x325	8150	
2007/03/07	16.29h	8	25x150	4100	
2007/03/07	16.41h	6	50x175	9000	
2007/03/07	16.54h	6	125x300	27650	
2007/03/07	20.28h	9	75x150	5400	
2007/03/08	08.34h	5	200x325	40500	
2007/03/08	08.47h	4	100x150	15000	*
2007/03/09	10.04h	12	25x75	1750	
2007/03/09	10.17h	12	25x75	2050	
2007/03/10	12.24h	11	25x75	2600	
2007/03/10	13.52h	11	25x125	2200	
2007/03/11	10.58h	12	25x125	2650	
2007/03/11	13.54h	11	50x125	5500	
2007/03/11	15.34h	12	25x75	2500	
2007/03/12	12.16h	11	25x75	1750	
2007/03/12	12.28h	11	25x75	2500	
2007/03/12	14.21h	11	25x100	1950	
2007/03/13	13.34h	14	25x50	1450	
2007/03/13	13.59h	12	25x75	1850	
2007/03/13	15.01h	12	25x50	1800	
2007/03/13	16.29h	12	25x75	1800	
2007/03/14	16.32h	12	25x50	2350	
2007/03/24	09.08h	14	25x50	1900	
2007/03/25	03.57h	6	25x225	5400	
2007/03/25	03.57h	9	25x100	4200	
2007/03/25	04.10h	6	75x200	9450	
2007/03/25	07.17h	5	50x150	7500	*
2007/03/25	07.54h	5	75x150	11250	*
2007/03/25	08.32h	5	50x150	7500	*
2007/03/25	08.44h	5	50x250	12500	*
2007/03/25	11.02h	9	25x100	3150	
2007/03/25	11.40h	3	125x400	18600	
2007/03/25	11.52h	5	100x200	7500	
2007/03/25	12.30h	6	100x300	14400	
2007/03/25	12.42h	6	150x325	28600	
2007/03/25	12.42h	3	125x275	14150	
2007/03/25	12.42h	4	25x75	2000	
2007/03/25	12.55h	5	50x200	10000	+
2007/03/25	13.07h	6	50x200	6600	
2007/03/25	13.32h	3	100x425	22400	
2007/03/25	13.45h	5	50x250	12500	*
2007/03/25	13.58h	6	50x150	7500	*
2007/03/25	14.35h	6	100x250	25000	*
2007/03/25	14.48h	4	25x50	2350	*
2007/03/25	15.00h	6	50x200	10000	*
2007/03/26	11.42h	7	25x50	1400	
2007/03/26	12.20h	11	75x125	7850	
2007/03/26	13.22h	6	50x200	10000	*
2007/03/26	13.48h	11	25x75	2150	
2007/03/26	14.00h	6	75x200	15000	*
2007/03/26	14.38h	9	50x150	6300	
2007/03/26	14.38h	10	25x75	2450	
2007/03/26	16.06h	3	25x125	2650	
2007/03/26	20.43h	6	25x200	5000	*
2007/03/26	22.12h	6	50x300	4700	*
2007/03/27	03.37h	9	50x150	7500	*
2007/03/27	04.02h	8	50x250	4150	
2007/03/27	04.14h	8	50x150	7500	+
2007/03/27	04.39h	3	125x200	20100	
2007/03/27	04.52h	6	50x200	10000	*
2007/03/27	05.29h	6	175x400	46700	
2007/03/27	05.29h	5	25x225	5250	
2007/03/27	05.42h	5	75x250	10150	
2007/03/27	05.42h	7	25x75	2350	
2007/03/27	06.07h	6	25x300	6650	
2007/03/27	06.19h	5	75x200	15000	*
2007/03/27	07.09h	5	50x150	7500	+
2007/03/27	07.21h	3	275x375	56650	
2007/03/27	07.21h	4	25x75	2050	
2007/03/27	08.24h	9	25x75	2100	
2007/03/27	09.02h	6	50x250	9000	
2007/03/27	09.14h	5	25x150	3750	+
2007/03/27	10.04h	3	100x375	21600	
2007/03/27	10.17h	3	150x375	25900	
2007/03/27	12.10h	6	50x275	7450	
2007/03/27	12.22h	7	50x75	3250	
2007/03/27	12.35h	11	50x125	6600	
2007/03/27	13.13h	5	25x150	3750	*
2007/03/27	13.38h	5	25x200	5350	
2007/03/27	14.15h	4	25x150	2950	
2007/03/27	14.28h	9	25x150	3750	*
2007/03/27	14.53h	11	25x75	1800	
2007/03/27	15.18h	4	25x100	2550	
2007/03/27	15.56h	5	75x250	18750	*
2007/03/27	16.09h	5	75x300	22500	*

2007/03/29	10.10h	12	25x100	2550	
2007/03/30	14.48h	6	50x275	11750	
2007/03/30	16.28h	6	50x275	11800	
2007/03/31	21.33h	6	50x200	10000	*
2007/03/31	21.46h	9	50x150	7500	*
2007/03/31	21.58h	9	75x175	7100	
2007/04/01	12.59h	11	25x100	2500	+
2007/04/01	13.11h	11	25x75	2100	
2007/04/01	13.24h	3	175x400	39600	
2007/04/01	13.49h	9	100x175	13400	
2007/04/01	14.02h	6	125x250	21750	
2007/04/01	14.14h	6	125x300	20600	
2007/04/01	14.27h	6	75x300	19350	
2007/04/01	22.52h	6	25x250	4000	
2007/04/02	00.58h	6	25x150	3850	
2007/04/02	12.37h	4	25x100	2250	
2007/04/02	12.50h	5	25x175	4600	
2007/04/04	03.19h	8	25x150	3750	*
2007/04/04	03.56h	5	100x275	11550	*
2007/04/04	04.33h	9	25x100	4000	
2007/04/04	04.58h	5	25x200	5000	*
2007/04/04	05.36h	6	50x200	10000	*
2007/04/04	07.40h	5	200x300	60000	*

As mentioned in the section Data archive (page 13), the images of the absolute value of the complex coherence corresponding to all the avalanches monitored are available in independent folders for an easier browsing.

- *DataAlagna\DataProcessed\Avalanches* contains the two-dimensional radar images of the absolute value of the complex coherence.
- *3DVisor\PPM_3DVisor* contains the three-dimensional radar images to be opened with specific vision software (*RadarDem[v2.0-1a].exe*).

Following is a short statistic of the avalanche events monitored. Figure 12 shows the histogram of the day (in the hydrological year) in which the avalanche events occurred. The plot on the left is a simple histogram while the plot on the right is the same histogram weighted by the size of the avalanches.

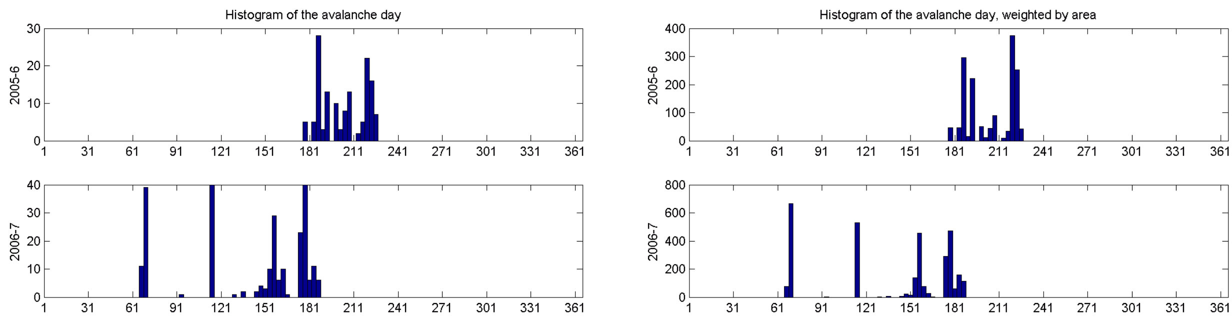

Figure 12: Histogram of the avalanche day in the hydrological year

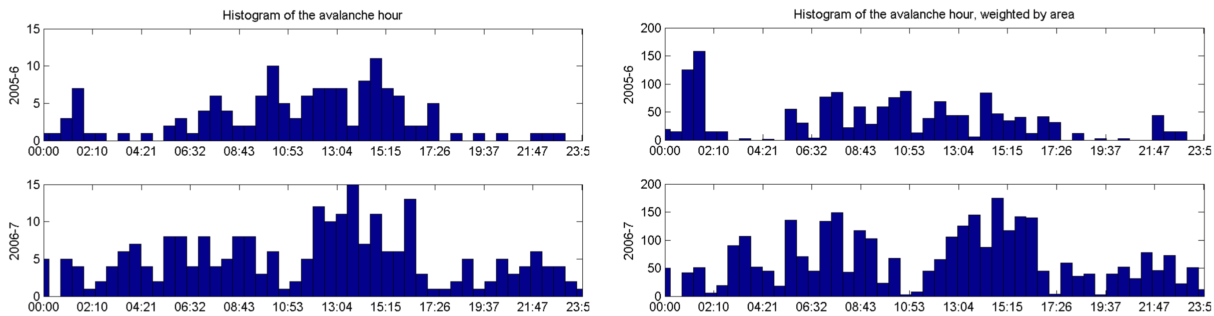

Figure 13: Histogram of the avalanche hour

Figure 13 shows the histogram of the time in which the avalanche events occurred, also as a simple histogram and a histogram weighted by the size of the avalanches. Figure 14 shows the histogram of the starting point of the avalanches according to the grid in Figure 9.

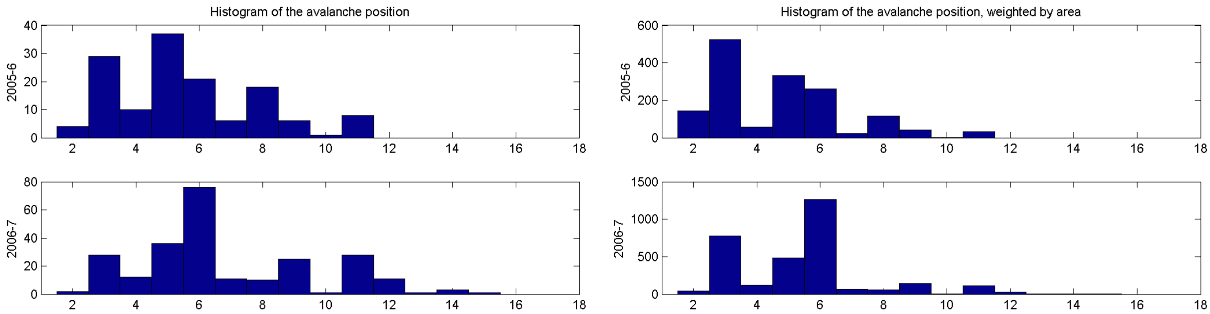

Figure 14: Histogram of the avalanche position

Finally, Figure 15 shows the histogram of the area in square meters of the avalanches monitored.

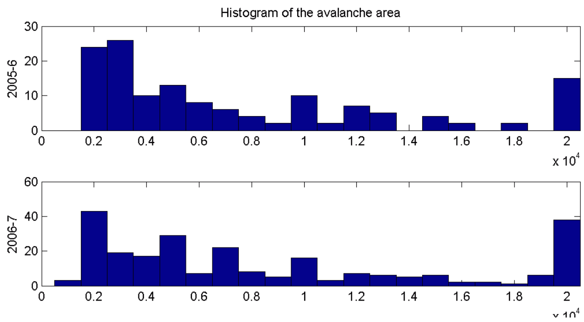

Figure 15: Histogram of the avalanche area in square meters

Concerning the day of the avalanches, it is not possible for the moment to draw conclusions since the data corresponding to both winters monitored has few days overlapping (see Figure 6). The distribution over the hour, however, is roughly uniform. The most active starting points for the avalanches correspond to positions 3, 5 and 6, that clearly are situated at the highest levels of the slope.

The histogram of the area involved in the avalanche paths shows typical areas close to 3000 m^2 and a considerable number of very big avalanches with an area bigger than 20000 m^2 (approximately 20 avalanches per year). Although the artificial avalanches are also included in these statistics, they represent only 2 out of the 385 avalanches listed in Tables 4 and 5. This shows that an important number of very big natural avalanches occur in this site.

Finally, Table 6 shows a summary on the number of days of field campaign and avalanches monitored with the LISA instrument.

Table 6: Summary of avalanches monitored

```
================================================
Winter 2005-2006: 2005/10/01-2006/09/30
    Field campaign days with LISA........:    73
    Images analyzed (NI)................:  8057
    Total avalanches identified with LISA:   140
Winter 2006-2007: 2006/10/01-2007/09/30
    Field campaign days with LISA........:   122
    Images analyzed (NI)................: 14742
    Total avalanches identified with LISA:   245

Totals:
    Field campaign days with LISA........:   195
    Images analyzed (NI)................: 22799
    Total avalanches identified with LISA:   385
```

Automatic identification

The list of avalanches shown on Tables 4 and 5 has been partially built with an automatic identification algorithm developed at the JRC of Ispra to retrieve possible avalanche events from GB-SAR imagery. In particular, avalanches not marked with an asterisk '*' or sum sign '+' on the `Mn` column where automatically identified and classified.

The algorithm uses the images of the absolute value of the interferometric coherence to look for the areas in the field-of-view where loose of coherence can be related to an avalanche event. To this aim five morphological parameters are defined in order to properly select the possible avalanches and discard artifacts present with a noisy background in the image. The parameters are listed in Table 7

Table 7: Parameters used to select spots candidates to avalanches

Parameter	Value	Description
`AxLen`	150	Minimum length of the major axis of the spots (m).
`Orient`	45	Minimum orientation of the major axis of the spot with respect to the horizontal (deg).
`AxRatio`	1.5	Minimum ratio of the major axis to the minor axis of the spot.
`MinArea`	1400	Minimum area of the object (m^2).
`MaxArea`	90000	Maximum area of the object (m^2).

And the formula for the selection of avalanche candidates is:

$$(\texttt{AxLen} \cup \texttt{AxRatio}) \cap \texttt{Orient} \cap \texttt{MinArea} \cap \texttt{MaxArea} \qquad (3)$$

Figure 16 shows an example of a coherence image (on the left) processed by the algorithm and giving as a result the labelled image on the right.

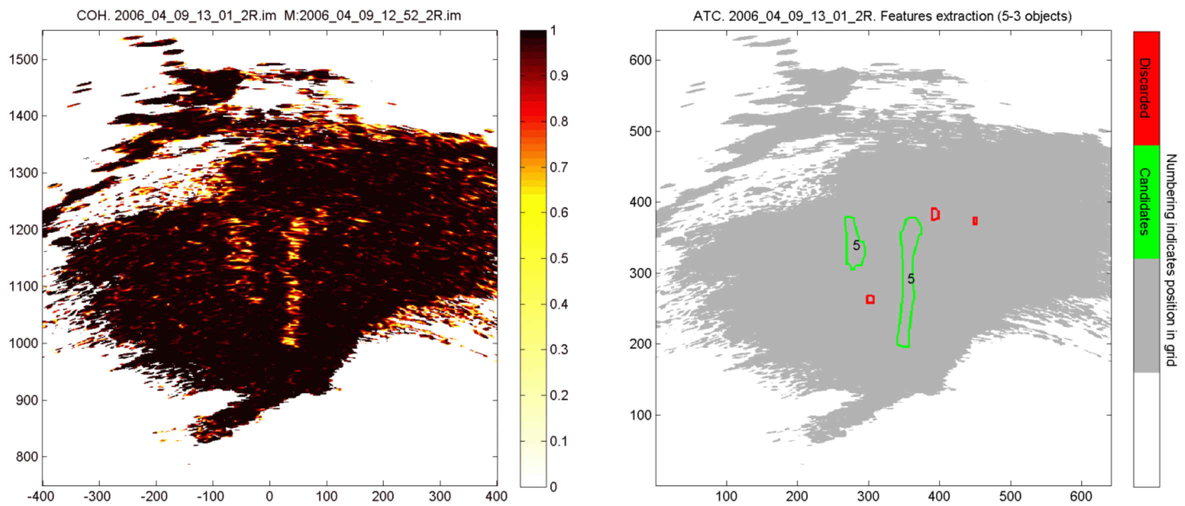

Figure 16: Coherence image and labelled image

It can be seen on the image on the right that five spots have been found on the intensity image with low values of coherence. From these, three of them marked in red have been discarded because of not satisfying eq.(3). The other two, marked in green, have been labelled with a 5, corresponding to the position in the grid of Figure 9 where the avalanches start.

Table 8 shows the algorithm performance for the data acquired during the two winter campaign. This summary is available in the DVD at *DataAlagna\FileList\flistOutSummary.txt*.

Table 8: Algorithm performance

```
================================================
Winter 2005-2006: 2005/10/01-2006/09/30
    Images analyzed (NI)................:  8057
    Avalanches candidates, auto (DA).....:   286
       Confirmed after supervission (MC).:   104
    Avalanches identified manually (AM)..:    36
       Far from automatic..........:   28
    Total avalanches identified with LISA:   140

Winter 2006-2007: 2006/10/01-2007/09/30
    Images analyzed (NI)................: 14742
    Avalanches candidates, auto (DA).....:   369
       Confirmed after supervission (MC).:   167
    Avalanches identified manually (AM)..:    78
       Far from automatic..........:   69
    Total avalanches identified with LISA:   245
================================================
Totals:
    Images analyzed (NI)................: 22799
    Avalanches candidates, auto (DA).....:   655
       Confirmed after supervission (MC).:   271
    Avalanches identified manually (AM)..:   114
       Far from automatic..........:   97
    Total avalanches identified with LISA:   385

    False positive rate, (DA-MC)/DA......: 58.6%
    False negative rate, AM/MC..... .....: 42.1%
    To supervise, DA/NI.................:  2.9%
```

Note that the false positive and false negative rates are relatively high. This is normal in such a kind of algorithms, where the most critical step is the thresholding of the intensity images in order to identify the possible avalanches. Unfortunately, in case of very adverse weather conditions, the identification of the possible avalanches can become difficult due to the highly noisy background in the image. Concerning the false negative rate (avalanches missed by the algorithm), a low value is particularly required in order to properly automate the identification process. For the Alagna site it has been observed that some of the avalanches not automatically identified happened very close in time to other avalanches properly identified (marked with a sum sign '+' in Tables 4 and 5). This implies that the operator, by just checking avalanches automatically identified can easily identify many of the avalanches missed by the algorithm. Nevertheless, its value continues being relatively high and work is still in progress in order to improve this rate.

The strength of the algorithm, however, is the reduced number of images to manually supervise, in the order of the 3%. Considering the huge amount of images generated by the radar this low rate represents an important time saving for the operator.

Ground-truth validation of the results

Unfortunately in this field campaign there has not been a systematic way to verify the avalanches identified by the LISA instrument other than meteorological data. Traditional means like geophones or high resolution visual imagery where not available in the site.

This implies that only avalanches showing a clear decrease on the coherences maps could be classified as avalanches, either automatically by the algorithm shown in the precedent section or manually by the inspection of the coherence images by an operator.

A system like the LISA instrument, with 24h continuous cycle work and even robust to bad weather conditions, makes it difficult a systematic assessment for the results provided. This brings the analysis of the data to experts both on the area of radar imagery and on the area of snow and ice. The synergy between both groups of experts is the best option, to the knowledge of the authors, for the evaluation of the results provided with a GB-SAR when monitoring the snow cover.

Skiers signature

A curiosity observed on the radar imagery is the signature of skiers or machines passing by the radar field-of-view. The signature is seen again as a loose of coherence, in this case with horizontal orientation. Figure 17 shows a couple of examples. Those images usually correspond to the days in which the ski resort is open to the public and close to noon time. In contrast, natural avalanches occur spread during the 24h of the day as has been shown on Figure 13.

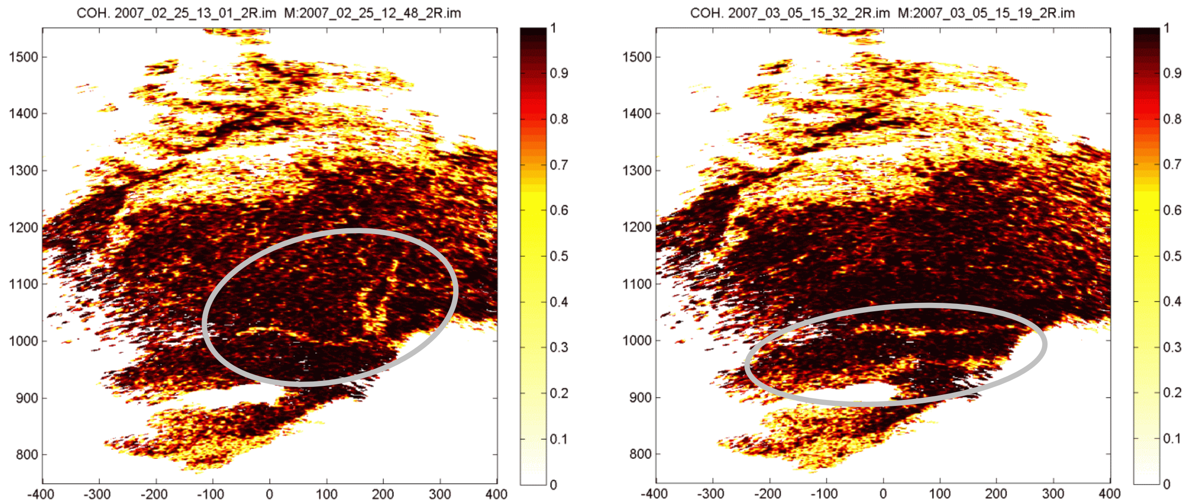

Figure 17: Skiers signature on the radar imagery

Hazard map

A practical product derived from the data processed is the hazard map obtained with the superposition (histogram) of the avalanches path in a whole winter season. These maps can be seen in Figure 18, where the image on the left corresponds to the winter 2005-2006 (period analyzed 2006/03/26 to 2006/05/15) and the image on the right corresponds to the winter 2006-2007 (period analyzed 2006/12/06-2007/04/04).

Dark red means that a high number of avalanches passed by the pixel of interest, yellow means a moderate-low number of avalanches occurred in the pixel, while gray (this is, the background mask) means no avalanche at all occurred in this pixel.

Unfortunately hazard maps result of difficult interpretation without a geo-referenced map or photo of the area used as background. In addition it is not possible to directly compare both images since the position of the radar system was slightly changed from the first to the second winter and thus the local reference system used for all the image formation. Note that the change of the radar position was motivated by the need to improve the image quality. During the first winter the system was located just over the ground, so snow accumulations in front of the radar created random and undesired reflections. During the second winter, instead, the system was elevated 2.8 m avoiding in this way any reflections with the snow or the ground.

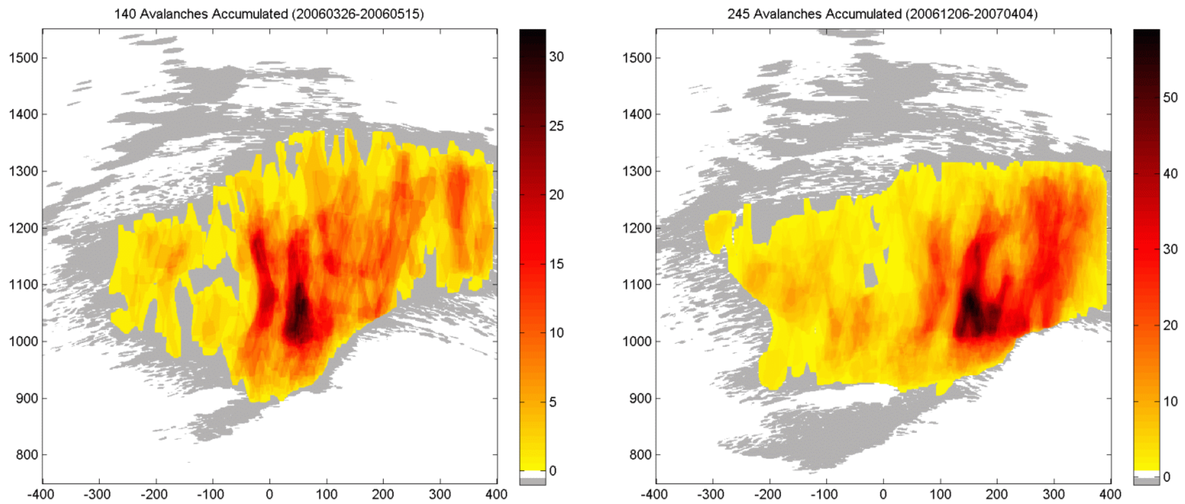

Figure 18: Hazard maps of the two winter seasons monitored

Nevertheless, the pixels with more avalanche activity (red ones) correspond to the natural corridors in the hill, characterized also by a big slope. The darkest area of both images corresponds to the same avalanche corridor. It can be seen how this corridor is divided into two smaller ones as the range decreases.

These pictures are available in the DVD at *DataAlagna\DataProcessed\HazardMap* and are available in 2D TIFF graphic format or PPM images for visualization with the three-dimensional vision software overlapped to a DEM.

Topographic mode

The two channels in reception vertically separated 80.5 cm allow the LISA instrument to work in its topographic mode. In this mode the system can generate digital elevation maps of the field-of-view at each acquisition. Figure 19 shows an example of DEM generated with LISA in its topographic mode the 2006/11/21 averaging a total of 200 images in order to reduce the phase noise.

While the avalanches are identified thanks to the systematic computation of interferograms using the double-pass interferometric mode of the LISA instrument (temporal baseline of 10 minutes), some attempts to obtain the snow volume displaced in an avalanche has been done using the topographic capabilities of the LISA instrument (single-pass interferometric mode, spatial baseline of 0.805 m). Once the avalanche instant is determined, the unwrapped interferometric phase obtained with the single-pass interferometric mode of the instrument is used to compute the DEMs of the focused zone just before and after the avalanche has occurred.

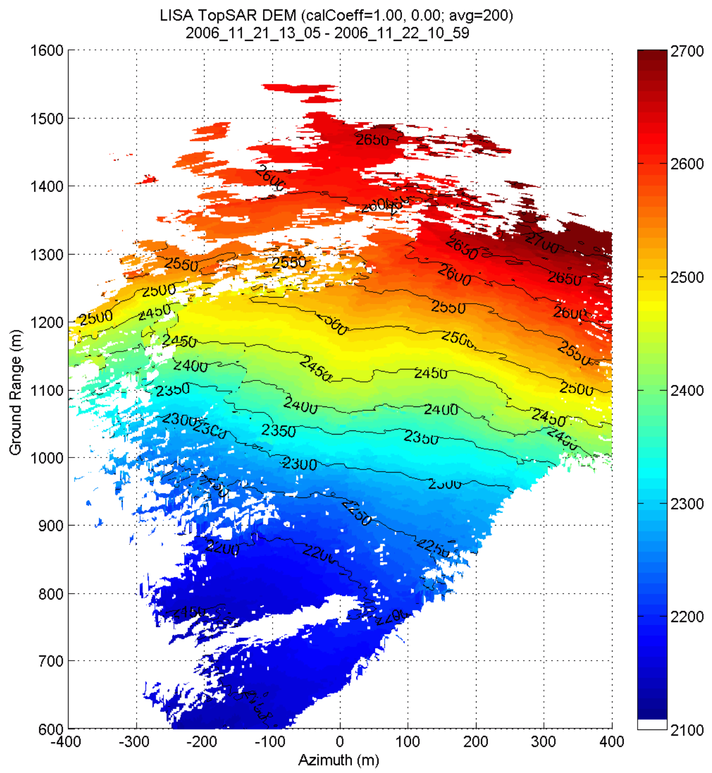

Figure 19: Digital Elevation Map generated with the topographic mode of the LISA instrument

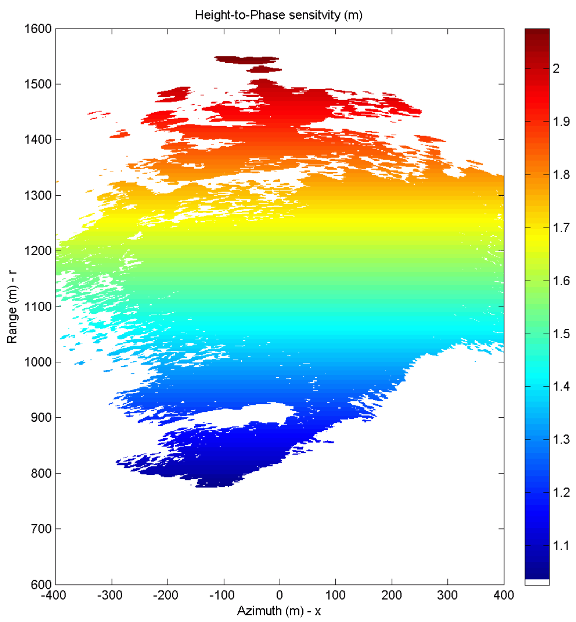

Figure 20: Height-to-phase sensitivity of the LISA instrument in Alagna

The differentiation of both DEMs gives as a result the volume of snow displaced in the avalanche event. Unfortunately the results are very noisy because of the low height-to-phase sensitivity of the instrument configuration. Figure 20 shows the sensitivity of the topographic mode of the instrument all along the focused area assuming a phase noise of 0.2 rad. The sensitivity ranges from 1 to 2 m approximately, so it is impossible to measure the typical differences of several centimetres that would arise on the snow cover after an avalanche.

This error is inherent to the small baseline of the instrument, so in its current configuration the only way to overcome this problem is through processing techniques. Averaging several images in order to reduce the sensitivity is the classical one, already tested without success. A more sophisticated averaging process in which noisy images are discarded has also been tested without success because the number of images required is so high that the temporal window spans several hours, loosing completely the coherence and hence the interferometric information.

The computation of the snow volume involved in an avalanche is, thus, not yet currently solved in such a system. Increasing the vertical separation of the two receiving antennas would definitely improve the height-to-phase sensitivity, but then the instrument would become less portable and much more instable: a vertical baseline of several meters would be required.

Follow up activities

The instrument used for monitoring the Olen valley at Alagna Valsesia is a similar replica of the instrument used to monitor the Sion valley in Switzerland during the winters from 2003 to 2006. This means that from the control software and hardware point of view most of the problems have been solved during the different field campaigns. The system is now able to work unattended during longs periods of time and even to automatically recover from errors or power supply inconsistencies. So at this point we can definitely state that the LISA instrument is perfectly mature for monitoring the snow cover.

On the processing part, instead, there is still some work to be done. First of all the algorithm for automatic avalanches identification and classification needs to be improved. Although a manual supervision will be always necessary and the algorithm in its current state reduces the images to supervise to only 3% of the acquired images, the false negative rate needs to be lower. Nevertheless, for the winter 2007-2008 campaign it is foreseen to include the before mentioned algorithm in the real-time processing chain of the instrument. This will allow the ski resort technical management to asses the utility of such results in their daily work of maintenance of their installations. This work is already supported by the real-time radar data visualization software installed on their offices, so the integration of the automatic avalanche identification algorithm will be seamless. The feedback of the end-user will be crucial for the improvement of the algorithm.

Concerning the retrieval of the snow volume displaced in an avalanche, a very important datum for snow avalanche modellers, it seems very difficult to improve the present accuracy without deeply modifying the hardware structure of the instrument. The way forward could be using a bistatic system composed of two LISA instruments. This represents, however, a new challenge since it has never been done, to the knowledge of the authors, with GB-SAR.

For hazard maps and the precise localization of avalanches, a ground-truth DEM and/or an orthophoto or geo-referenced map would be of very much utility. Right know radar images are projected over a white background on the local reference system of the instrument. This makes the interpretation of the results harder than in the case where visual references would be available. It appears feasible to have the DEM ready for the next winter campaign, since some contacts have already been established with another research group of the JRC in possession of a laser scanner and with a private enterprise offering the services of 3D modelling.

An important pending task is still the necessity to assess all the avalanches detected by LISA. This job is expected to be carried out by a group of experts covering not only the radar side but particularly the snow cover study. In addition, a means of obtaining ground-truth data needs to be defined in order to systematically assess the avalanches retrieved by the instrument.

To this aim, a collaboration agreement already started during the last months of the current campaign with the Department of Exploitation and Protection of the Agricultural and Forestry Resources (DI.VA.P.R.A.) of the University of Turin is expected to be further developed during the next winter campaign 2007-2008. This group of experts, lead by Michele Freppaz and Margherita Maggioni, develops their research activity on the fields of ice and snow at the Istituto A. Mosso, at the top of the Olen valley, Passo dei Salati.

Meteorological data, available for the whole campaign, has not yet been exploited. This data needs also to be correlated with the radar observations, and this task is expected to be supervised by the experts of the University of Turin for the next winter campaign.

Although the LISA instrument has performed excellently during these 2 winters field campaign, there is also one aspect that could be improved with considerable advantageous consequences. A reduction of the acquisition time would imply a higher quality on the images generated and the possibility to study in more detail the dynamics of avalanches. This could also evidence avalanche precursors not available with the current data archive. The SERAC Unit is currently working on this improvement through the use of antenna array systems instead of mechanically moved antennas and the evaluation of new hardware platforms.

Conclusions

The field campaign described in this report has provided, to the knowledge of the authors, the second archive of ground based synthetic aperture radar (GB-SAR) imagery for the study of the snow cover. The first one was obtained also with a LISA instrument by the same authors during a field campaign of 3 winters in the Sion valley (Switzerland) from 2003 to 2006.

Different radar signatures are present in the archive, such as those corresponding to natural avalanches, artificially triggered avalanches, snow drift, skiers passing by, etc. corresponding to two winter seasons. Unfortunately no ground truth other than meteorological data is available, and this is probably the biggest weakness of the campaign from the scientific point of view.

Nevertheless the more promising utility of the system will be put on practice for a new field campaign covering the winter 2007-2008: the systematic and automatic avalanche identification and classification. This campaign will imply a closer collaboration with snow experts, so it is expected that the algorithm will improve enough to become functional and at the same time synergies between both engineers and snow experts could lead to new ideas and products. Ground truth data is expected to be collected also by snow experts of the University of Turin, complementing in this way the radar acquisition and allowing the validation of results.

The main conclusion is that the potential to use GB-SAR systems for the monitoring of the dry snow is confirmed again by this field campaign. Hardware and control software parts are very mature, while data processing needs still some time to become robust and of practical utility.

Acknowledgements

The authors would like to thank for their collaboration in the different tasks of setting up the system in Cimalegna the technical personnel of the Alagna ski resort and in particular Claudio Francione and Andrea Colla from Monterosa 2000 S.p.A and the local Alpine Guides Michele Cucchi and Nicola Viotti.

We would also like to thank Dario Tarchi, Marco Basso, Jorge Morgado and Gian Luigi Ruzzante from DG JRC (Ispra, Italy) for their support in this campaign.

List of publications

During this field campaign several scientific ([6] and [8]) and non-technical ([7]) publications have been produced. Two of them correspond to conference papers with their corresponding attendance and public presentation: [6] and [7]. A regular manuscript is currently being prepared to be submitted to the IEEE Geoscience and Remote Sensing journal, regarding the specific automatic avalanche identification system being implemented for the next winter season.

The rest of publications listed below correspond to the know-how gained by the SERAC Unit in the field of snow cover monitoring with GB-SAR, in the course of other field campaigns.

[1] A. Martinez-Vazquez; J. Fortuny-Guasch; U. Gruber; *Monitoring of the Snow Cover with a Ground-Based Synthetic Aperture Radar*. 4th EARSeL Special Interest Group on Land Ice & Snow (LIS-SIG) Workshop eProceedings 4 2/2005, Bern (Switzerland), February 2005.

http://las.physik.uni-oldenburg.de/eProceedings/vol04_2/04_2_martinez1.html

[2] A. Martinez-Vazquez; J. Fortuny-Guasch; *Monitoring Structural Changes and Stability of the Snow Cover with a Ground-Based Synthetic Aperture Radar*. URSI 2005 Commission F Symposium, Barza d'Ispra (Italy), April 2005.

http://ursi-f-2005.jrc.it/fullpapers/URSI-F-2005-Art_7.3.pdf

[3] A. Martinez-Vazquez, J. Fortuny-Guasch; *Avalanche And Snowfall Monitoring With A Ground-Based Synthetic Aperture Radar*. 4th International Workshop on ERS SAR Interferometry FRINGE 2005, November 2005.

http://earth.esa.int/workshops/fringe2005/proceedings/papers/23_martinezvazquez.pdf

[4] A. Martinez-Vazquez, J. Fortuny-Guasch; Snow Cover Monitoring in the Swiss Alps with a GB-SAR. IEEE Geoscience and Remote Sensing Society Newsletter, March 2006, pp.11-14.

http://www.grss-ieee.org/files/grsNL0306.pdf

[5] A. Martinez-Vazquez, J. Fortuny-Guasch; Feasibility of Snow Avalanche Volume Retrieval by GB-SAR Imagery. Geoscience and Remote Sensing Symposium, 2006. IGARSS '06 Denver. Proceedings.

[6] A. Martinez-Vazquez, J. Fortuny-Guasch; *Snow Avalanche Detection and Classification Algorithm for GB-SAR Imagery*. Geoscience and Remote Sensing Symposium, 2007. IGARSS '07 Barcelona. Proceedings.

[7] G. Antonello, A. Martinez-Vazquez, J. Fortuny-Guasch, M. Freppaz, M. Maggioni; *Il radar "LISA" per le valanghe*. Magazine Neve e Valanghe of the Associazione Interregionale Neve e Valanghe (AINEVA). November 2007, Italy.

[8] G. Antonello, A. Martinez-Vazquez, J. Fortuny-Guasch, M. Freppaz, M. Maggioni; *Il Monitoraggio delle Valanghe con il GB-SAR LISA ad Alagna Valsesia*. 11a Conferenza Nazionale ASITA, November 2007, Torino (Italy).

Conference Attendance

[1] Risk Mitigation of Slope Instability Workshop, Ispra (Italy), 2004, 30 September to 1 October.

[2] EARSeL Special Interest Group on Land Ice & Snow (LIS-SIG) 4th Workshop, Bern (Switzerland), 2005, 21-23 February.

[3] URSI Commission F Symposium on Microwave Remote Sensing of the Earth, Oceans, Ice and Atmosphere, Barza d'Ispra (Italy), 2005, 20-21 April.

[4] FRINGE 2005 Workshop. Advances in SAR Interferometry from ENVISAT and ERS missions, ESA ESRIN Frascati (Rome, Italy). 2005, 28/November - 2/December.

[5] IEEE International Geoscience and Remote Sensing Symposium, Denver (Co), USA, 2006, 21/July - 4/August.

[6] IEEE International Geoscience and Remote Sensing Symposium, Barcelona, Spain, 2007, 23 - 27/July.

[7] Federazione delle Associazioni Scientifiche per le Informazioni Territoriali ed Ambientali, ASITA. 11a Conferenza Nazionale, Torino (Italy), November 2007.

European Commission

EUR 22947 EN – Joint Research Centre – Institute for the Protection and Security of the Citizen
Title: Two Winters of Snow Monitoring with the LISA Instrument in Alagna Valsesia - Val d'Olen (I): 2005-2007
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Abstract
This document presents the activities carried out with the LISA system during the winters 2005-2006 and 2006-2007 in the ski resort of Alagna Valsesia (Italy, Piedmont region), in collaboration with the technical personnel of the ski resort (Monterosa 2000 S.p.A) and the local Alpine Guides.
Results include the systematic identification and classification of avalanches, visualization of skiers' tracks, production of hazard maps and the generation with the LISA instrument of a digital elevation map of the area.

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